

# Simulation-based energetic building design with different detailed and adaptive modeling hierarchies

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Presentation during research visit at LBNL, August/September 2011



Universität der Künste Berlin, Institut für Architektur und Städtebau  
Prof. Dr.-Ing. C. Nytsch-Geusen



# My simulation research in Berlin, Germany

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- **Institute of Architecture and Urbanism, University of the Arts Berlin** (<http://www.arch.udk-berlin.de>)

- Chair for Building Services Engineering
  - Head of a building simulation Group
    - Model development, model integration, co-simulation, model application



- **Fraunhofer Institute for Computer Architecture and Software Technology** (<http://www.first.fraunhofer.de>)

- Consultant of my former simulation group
    - Applied simulation research projects, Modelica language and Modelica-compilers, 3D visualisation of simulation models



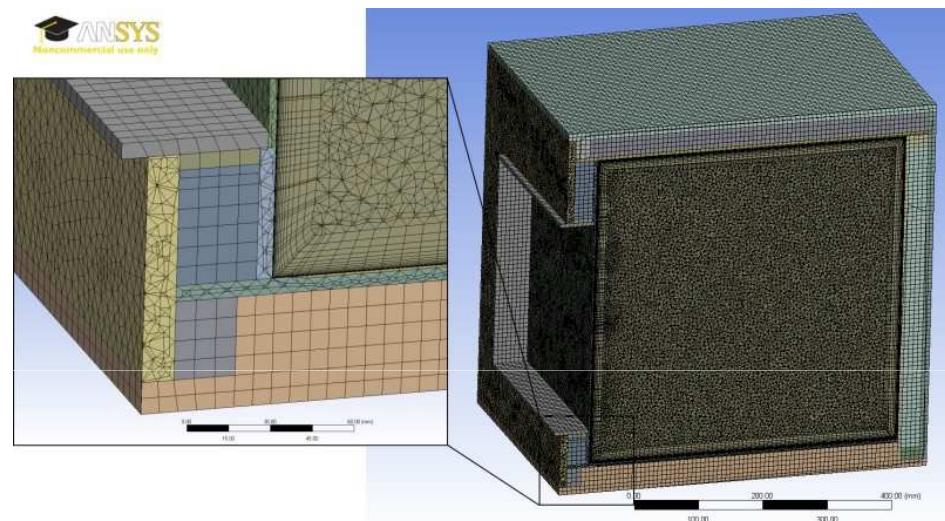
# Motivation – “Close to the reality simulation”

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Example: High-resolution 3D model of a thermal model house



Mobile test facility for studying effects of room air conditioning (<http://www.thermisches-modellhaus.de>)



Cut through a 3D model of the thermal model house, based on ANSYS CFD

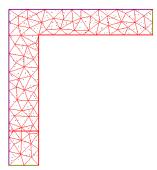
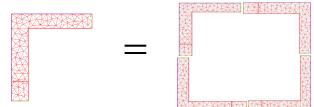
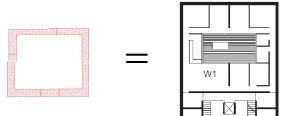
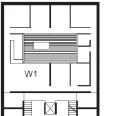
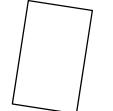
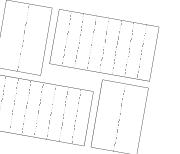
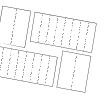
Use of the Finite Volume Method:

- 1.1 million elements for the building envelope
- 7.2 million elements for the enclosed air



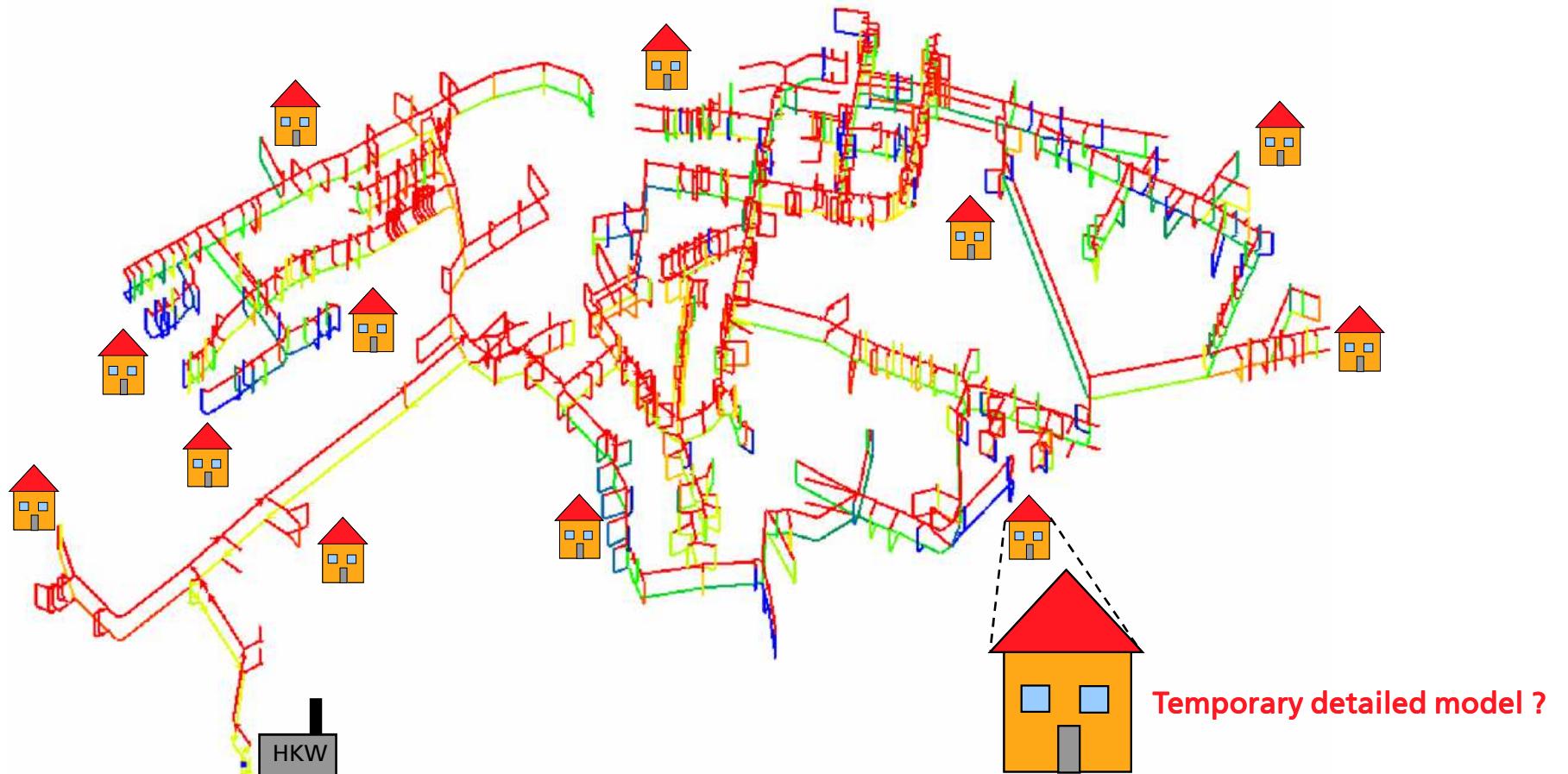
# Motivation – Simulation of complex building systems

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<b>Building Component</b>	$1 \times$		$\rightarrow 144$ state variables (equal to number of finite elements, if pure heat conduction is assumed)
<b>Room</b>	$4 \times$	 = 	$\rightarrow 576$ state variables
<b>Apartment</b>	$8 \times$	 = 	$\rightarrow 4,608$ state variables
<b>Apartment house</b>	$4 \times$	 = 	$\rightarrow 18,432$ state variables
<b>Sub-Neighbourhood</b>	$20 \times$	 = 	$\rightarrow 368,640$ state variables
<b>District</b>	$25 \times$	 = 	$\rightarrow 9,216,000$ state variables



# Motivation - Adaptive system simulation



A system model of a district heating network (city Rheinsberg, Germany), based on simplified component models (energy central, hydraulic distribution system, 500 building models) leads to 40.000 state variables

→ Transient system simulations, based on detailed sub-models are not possible with static model structures



# Agenda

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## 1. Multiscale Simulation

- Cross-validation of simplified models with detailed models
  - Example: Pipe redirection
- Model scaling according to the simulation issue
  - Example: Model hierarchies “Component” – “Building” – “City district”

## 2. Co-Simulation

- Numerical coupling of 1D- and 3D-models
  - Example: Solar thermal system

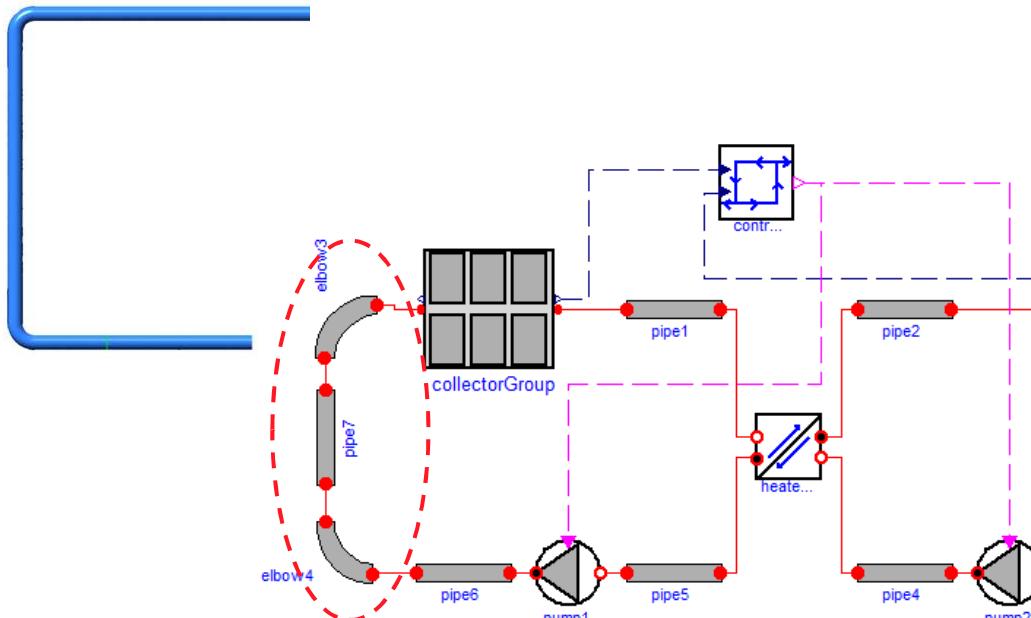
## 3. Adaptive Simulation

- Use of “Model Structural Dynamics”, based on Modelica
  - Example: Solar heating system with an adaptive building model

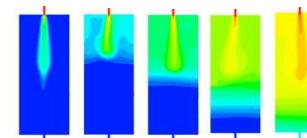


## Multiscale Simulation – Cross-Validation of simplified models with detailed models

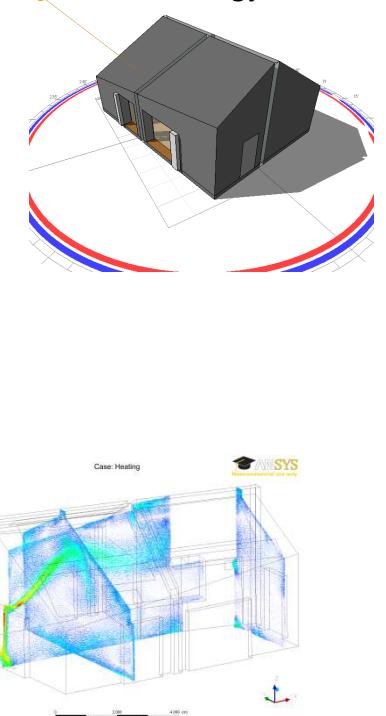
**Comparative 3D-CFD analysis  
of the pressure losses for the  
standard hydraulic components**  
(ANSYS CFD)



**Comparative 3D-CFD analysis  
of the thermo-hydraulic  
behaviour of thermal storages**  
(ANSYS CFD)



**Comparative multi-  
zonal analysis of the  
energy performance  
of the building**  
(ECOTECT/EnergyPlus)



**One-dimensional, component based simulation analysis of energy supply systems**  
(Modelica tool with DAE solver + specific Modelica libraries + Modelica system model)

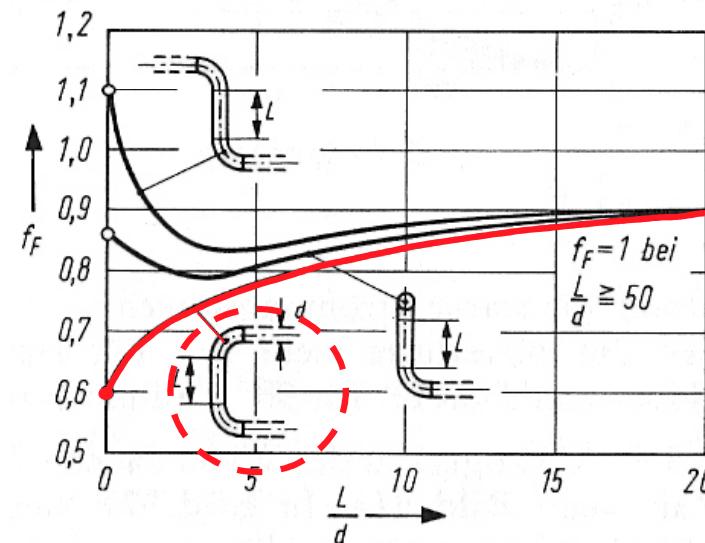
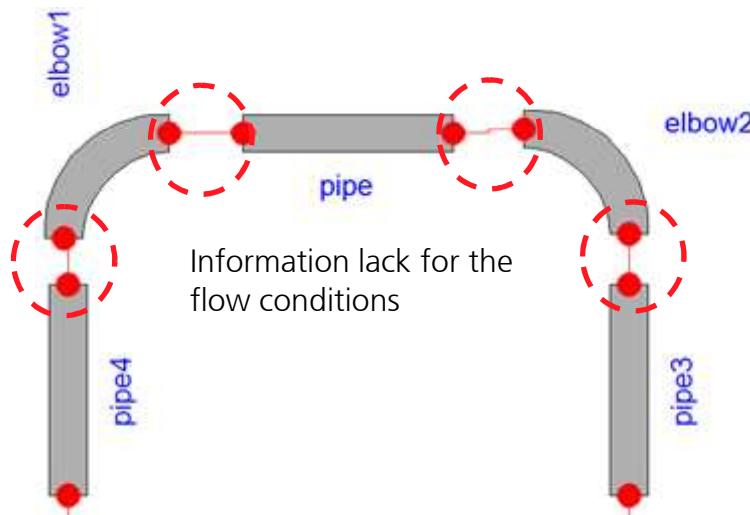
**Comparative 3D-CFD analysis  
of the air flow condition  
within the building zones or  
around the building**  
(ANSYS CFD)



# Multiscale Simulation – Example: Pipe Redirection

## – Pressure loss calculation of connected component models

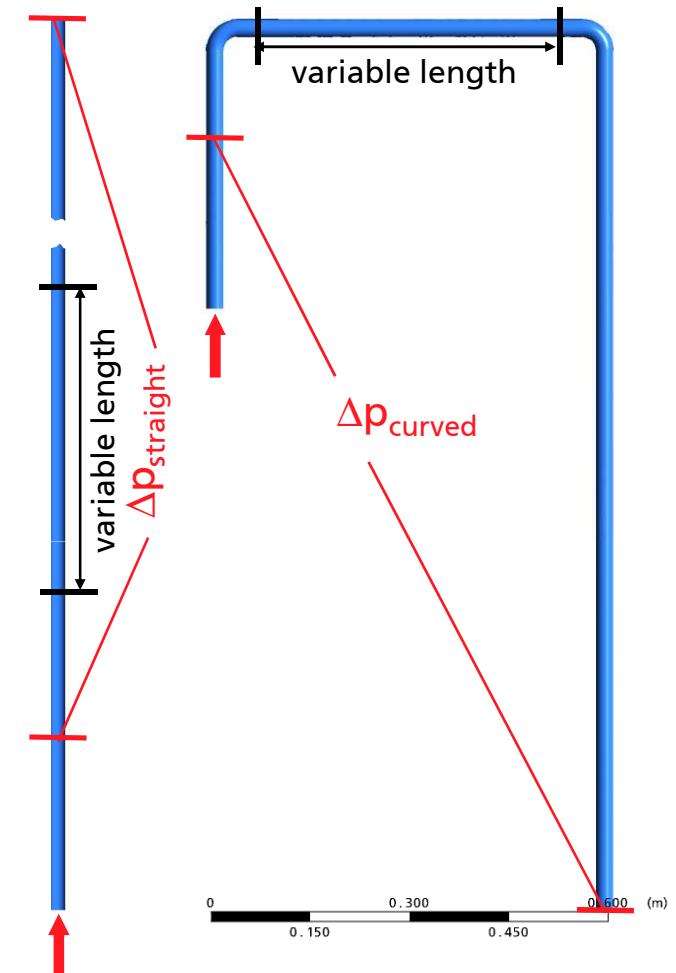
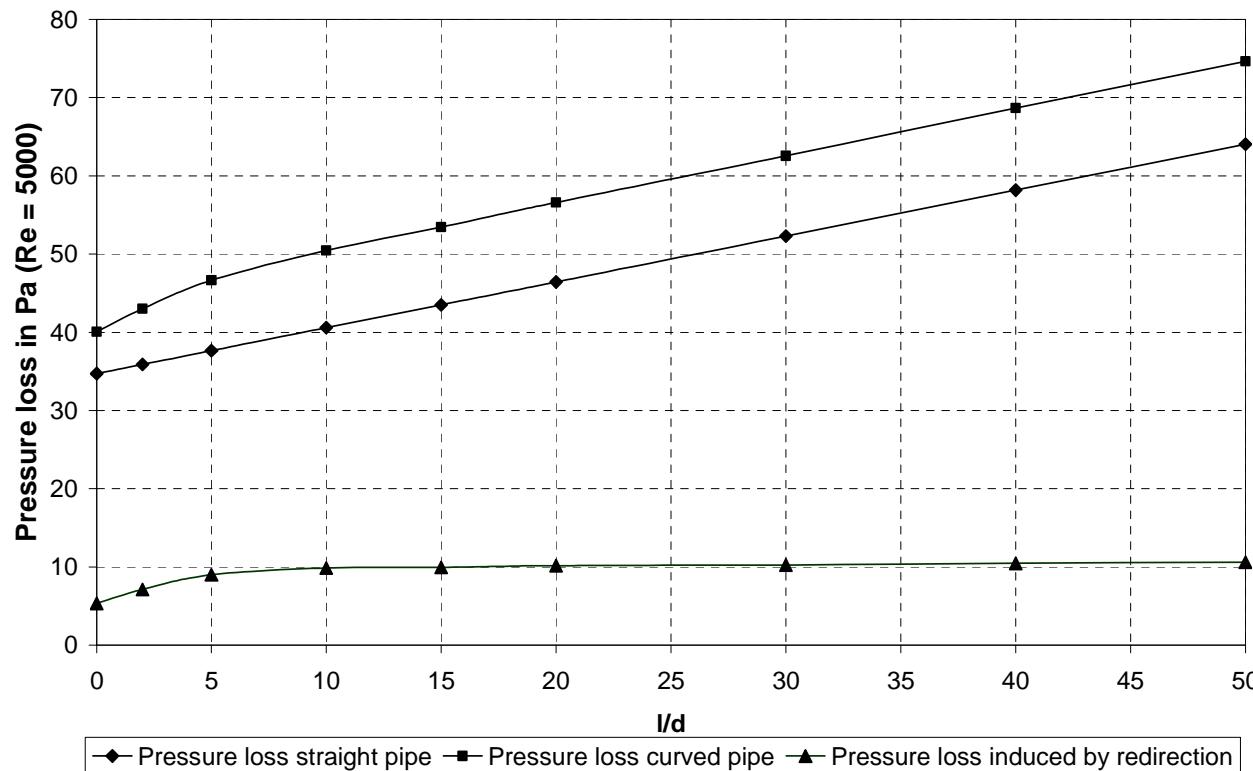
- Component-based approaches (e.g. Modelica) can not really consider the flow conditions (flow profile, turbulence intensity) between connected hydraulic components
- Introduction of correction factors  $f_F$  for the pressure loss calculation



Results from experiments for the  $f_F$ -factor (Source: Wagner)



# Multiscale Simulation – Example: Pipe Redirection

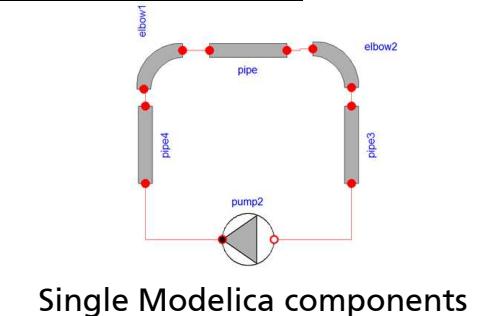
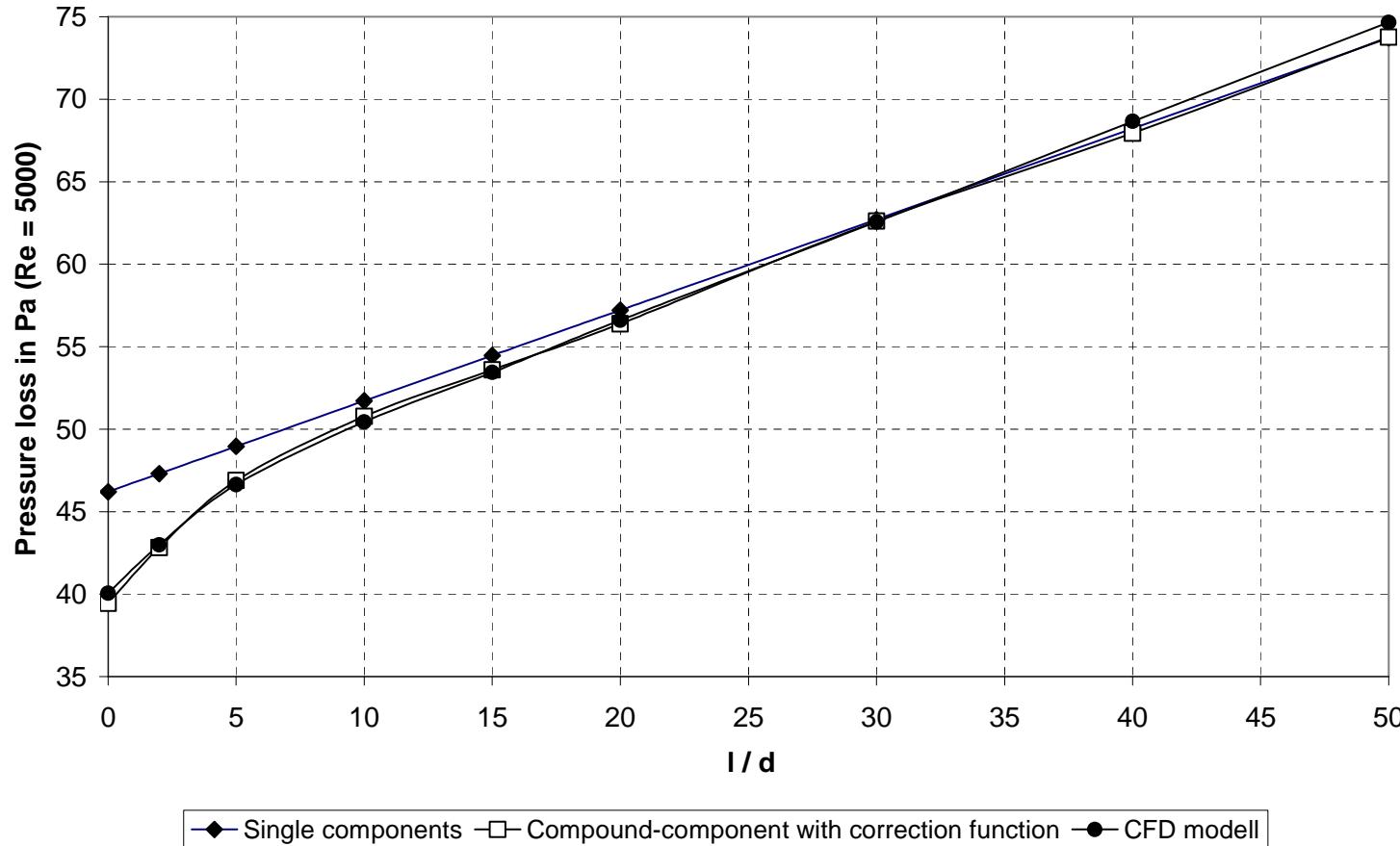


- Comparative simulation of the pressure loss with Modelica and CFD for a curved pipe ( $\Delta p_{straight}$ ) and a straight pipe ( $\Delta p_{curved}$ ) with the same length
- Results:  $f_f$ -factors for Re-numbers between 100 – 100,000

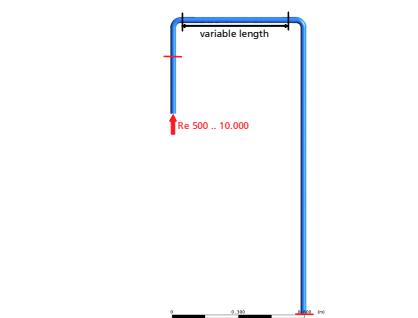
3D-CFD-model of a straight pipe and of two 90° elbows with an intermediate pipe



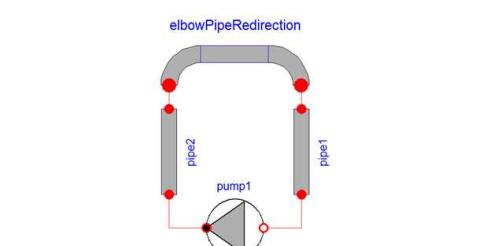
# Multiscale Simulation – Example: Pipe Redirection



Single Modelica components



CFD model (ANSYS CFD)



Compound Modelica model with the correction equation

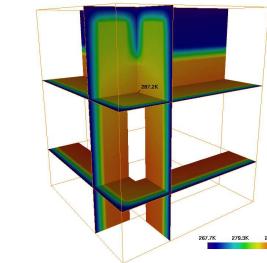
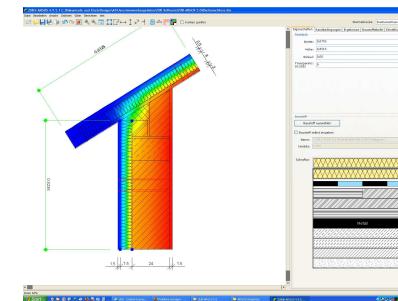
→ The improved model needs only one more “correction equation”



# Multiscale Simulation – Model scaling according to the simulation issue

## – Component hierarchy

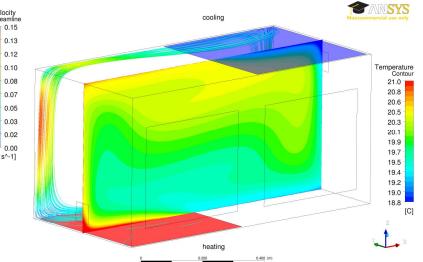
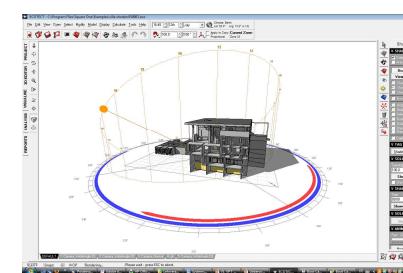
- Problems: Heating bridge effects, thermal-hygric component analysis
- Tools: ARGOS, WUFI, KARDOS, ANSYS, ...



Component simulation (ARGOS, KARDOS)

## – Building hierarchy

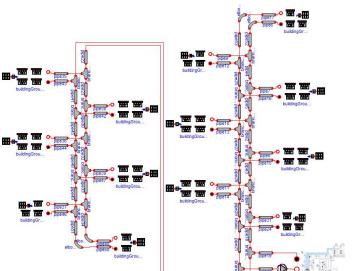
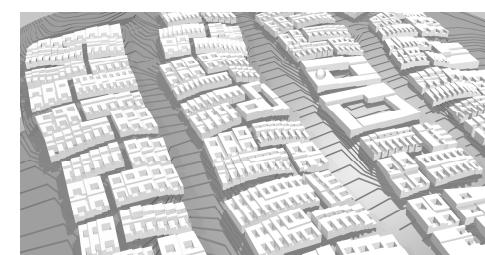
- Problems: Energy demand analysis, heating and cooling loads analysis, control strategies development, thermal comfort analysis, HVAC system design
- Tools: Autodesk ECOTECT, EnergyPlus, ANSYS-CFD, Modelica, ...



Building simulation (Autodesk ECOTECT, ANSYS CFD)

## – City/District hierarchy

- Problems: Energy supply concepts and energy management on district level
- Tools: Autodesk ECOTECT, Modelica, CitySim



Infrastructure simulation at the district level (Modelica)



# Multiscale Simulation – Example: Component hierarchy

- Development of a multi-storey „Passivhaus“ residential building in solid wood construction
  - Competition IBA 2013, Hamburg
  - Smart Price (building construction, material selection, HVAC)
  - High degree of prefabrication
- Energy concept
  - Building envelope:  
→ **Minimization of the heating bridge-effects by simulation analysis**
  - HVAC-Technology: Air heating with heat recovery system and earth heat thermal Solar energy production

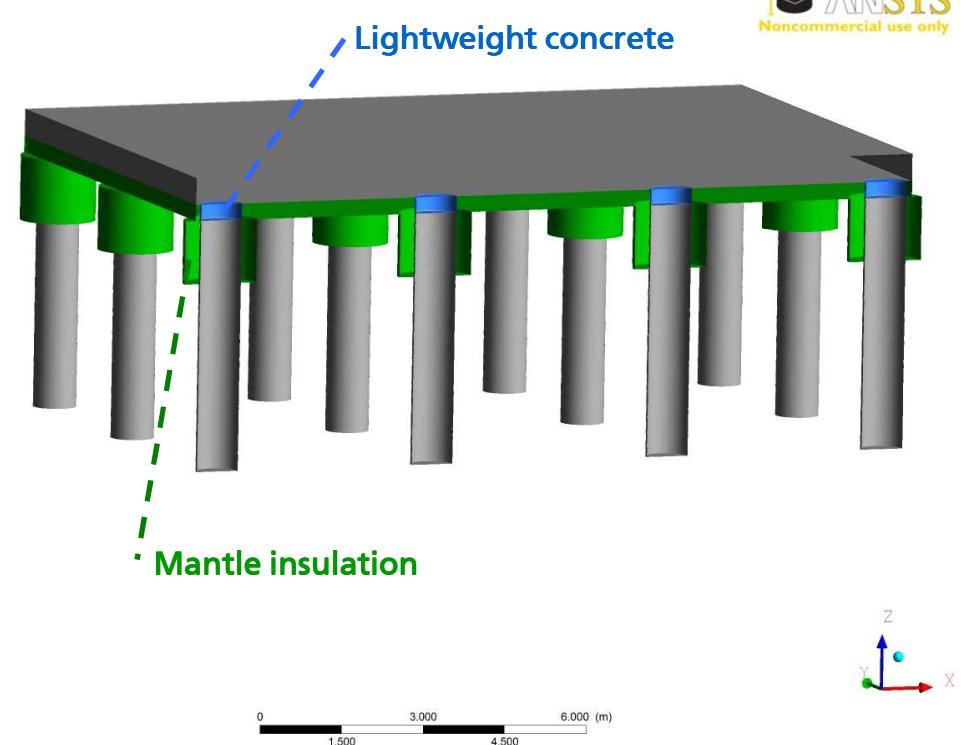
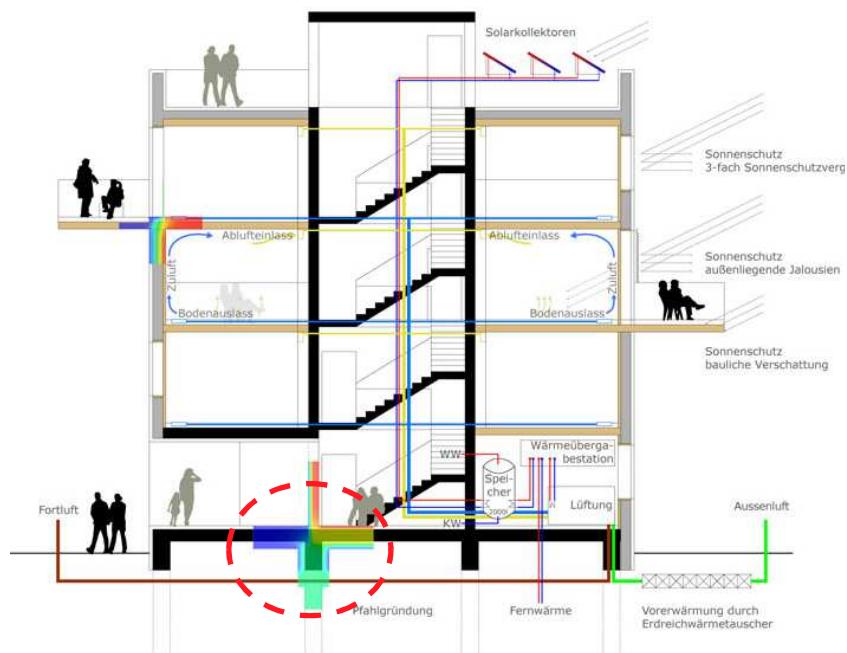


Multi-storeyd Passivhaus-residential building WOODCUBE in solid wood construction(Quelle: IfUH)



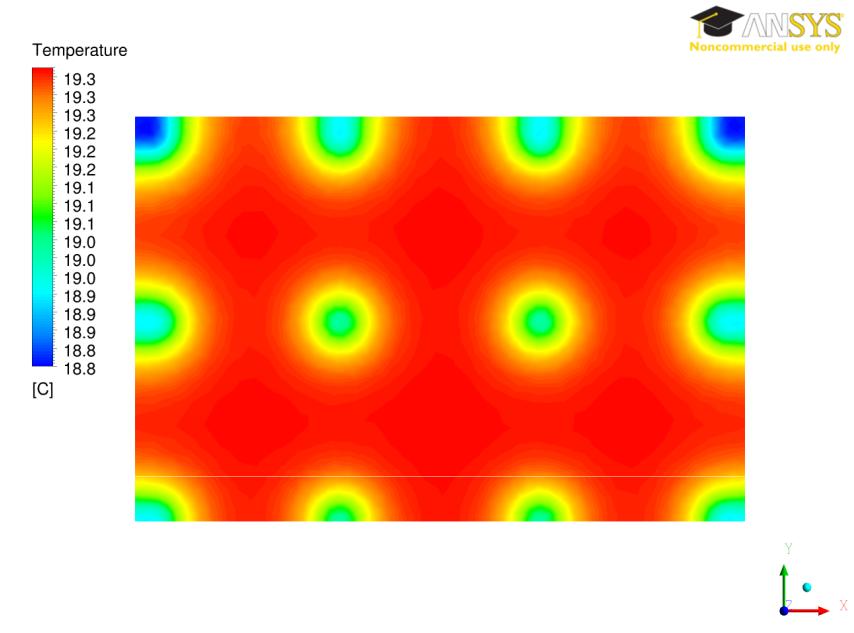
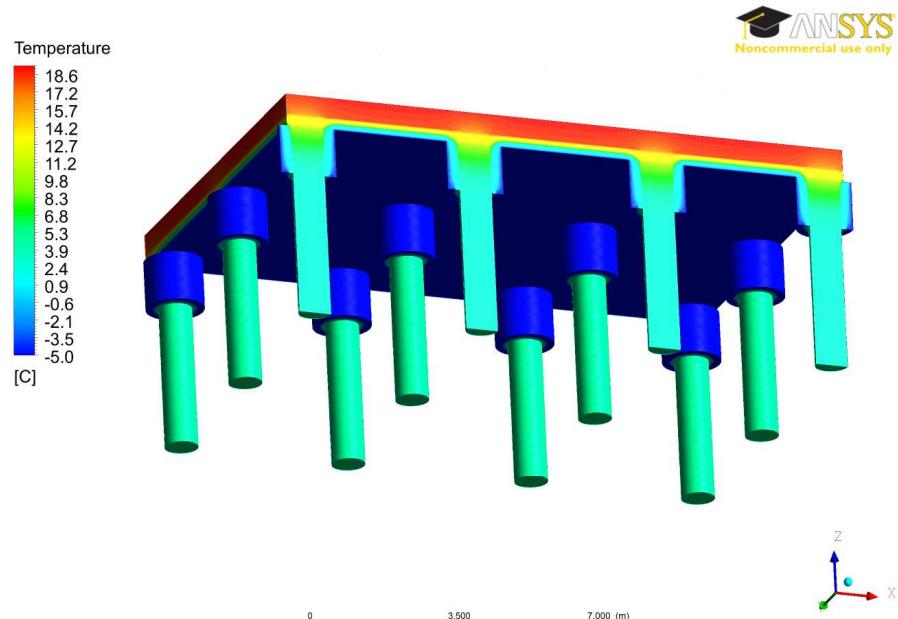
# Multiscale Simulation – Example: Component hierarchy

- Stationary 3D-heating bridge analysis for the floor plate construction, based on ANSYS
  - Interaction of structural design and building physics



# Multiscale Simulation – Example: Component hierarchy

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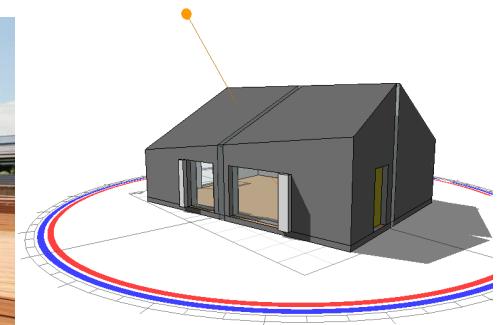


- Heat losses with ideal out side insulated ground slab  
(without the heat bridges of the columns): 100 percent
- Heat losses with improved insulated ground slab  
(thermal separation and insulation of the columns): 108 percent

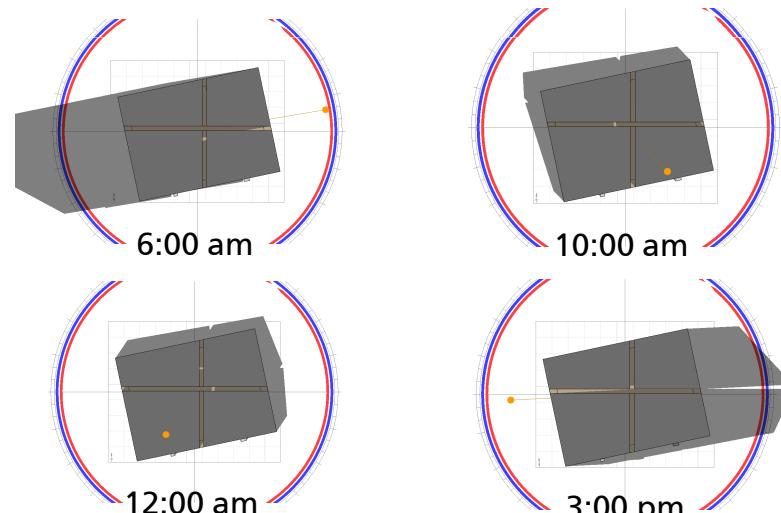


# Multiscale Simulation – Example: Building hierarchy

- International student competition „Solar Decathlon Europe“ in Madrid (June 2010)
  - Development of small zero-energy residential buildings by student teams
- Berlin team „Living Equia“
  - 30 students from 3 universities of Berlin developed a building with 46 m<sup>2</sup> floor space
  - Envelope: solid wood construction, PCM-clay interior ceilings
  - Building technology: DEC-air conditioning, small heat pump, cooling/heating by air and surfaces, photovoltaic + solar thermal energy production
- Simulation analysis during the planning process
  - Calculations with ECOTECT/EnergyPlus and ANSYS CFD
  - **Shading and radiation analysis produces boundary conditions for thermal CFD analysis**



„Living Equia“ building in Madrid and the used Autodesk ECOTECT building model for the radiation analysis

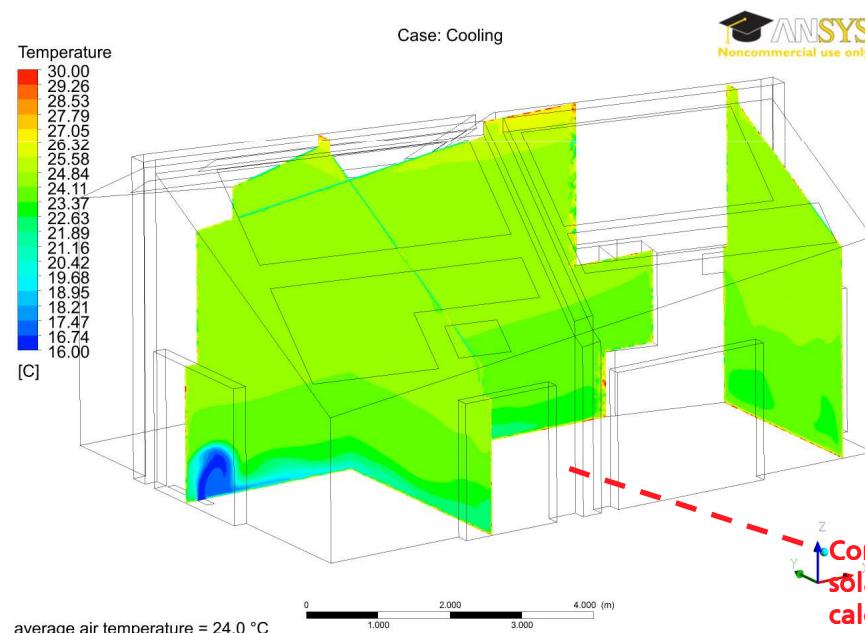


Shadow pattern during June 1st in Madrid

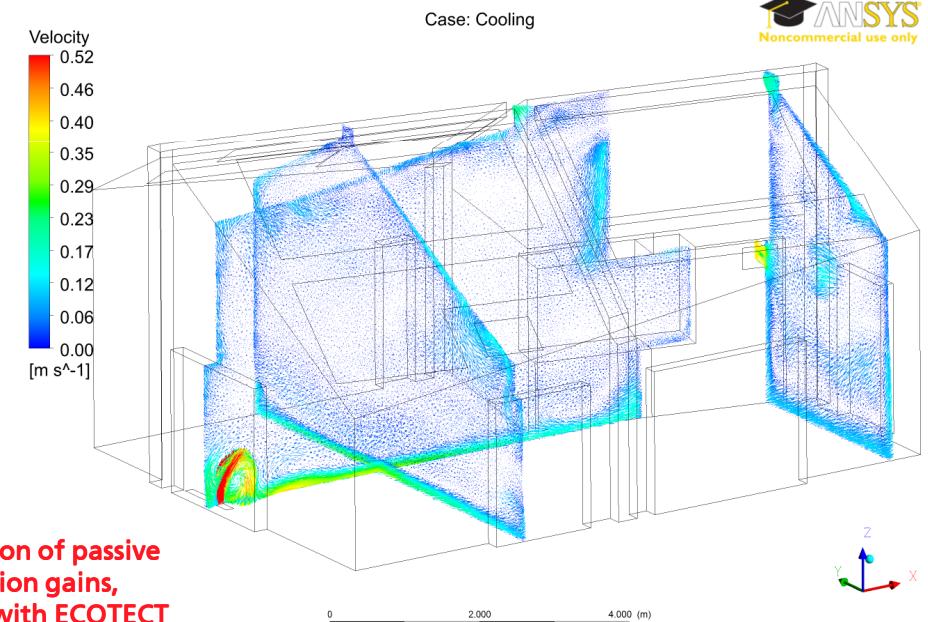


# Multiscale Simulation – Example: Building hierarchy

- Stationary 3D-simulation for the cooling case (location Madrid), based on ANSYS CFD
  - Outside air temperature: 37.5 ° C
  - Mean set-air temperature: 25 ° C
  - Supply air temperature: 16 ° C
  - Mean cooling ceiling temperature: 20,1 ° C



Temperature distribution for the cooling case (location Madrid)



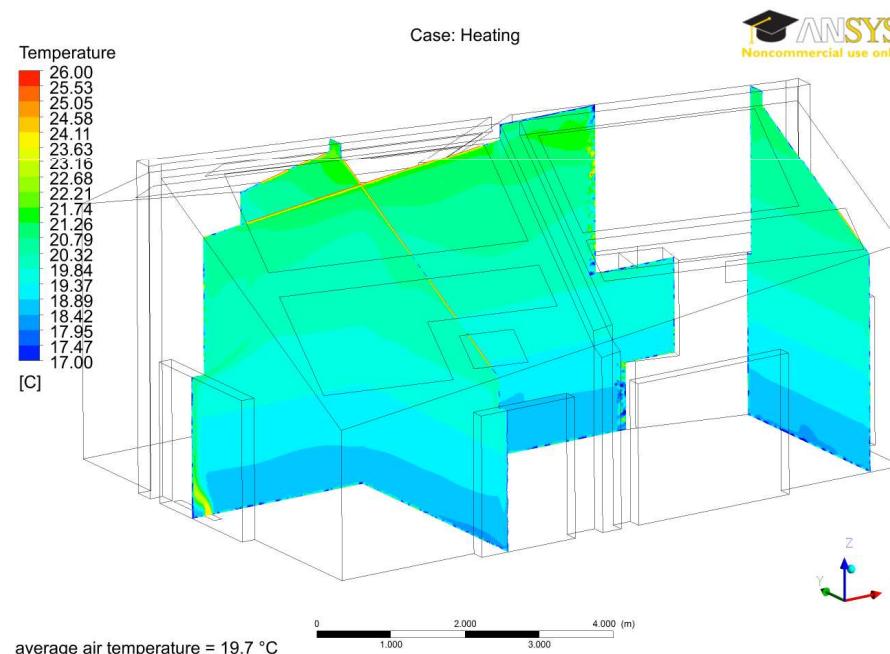
Velocity distribution for the cooling case (location Madrid)



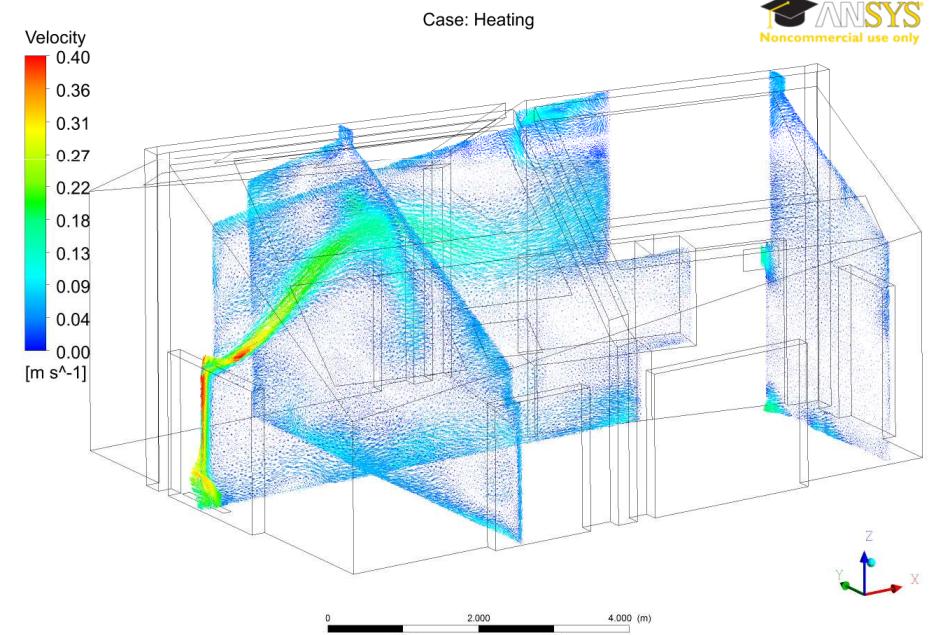
# Multiscale Simulation – Example: Building hierarchy

## – Stationary 3D-simulation for the heating case (location Berlin), based on ANSYS CFD

- Outside air temperature: - 14 ° C
- Mean set-air temperature: 20 ° C
- Supply air temperature: 24 ° C
- Mean heating ceiling temperature: 25,6 ° C



Temperature distribution for the heating case (location Berlin)



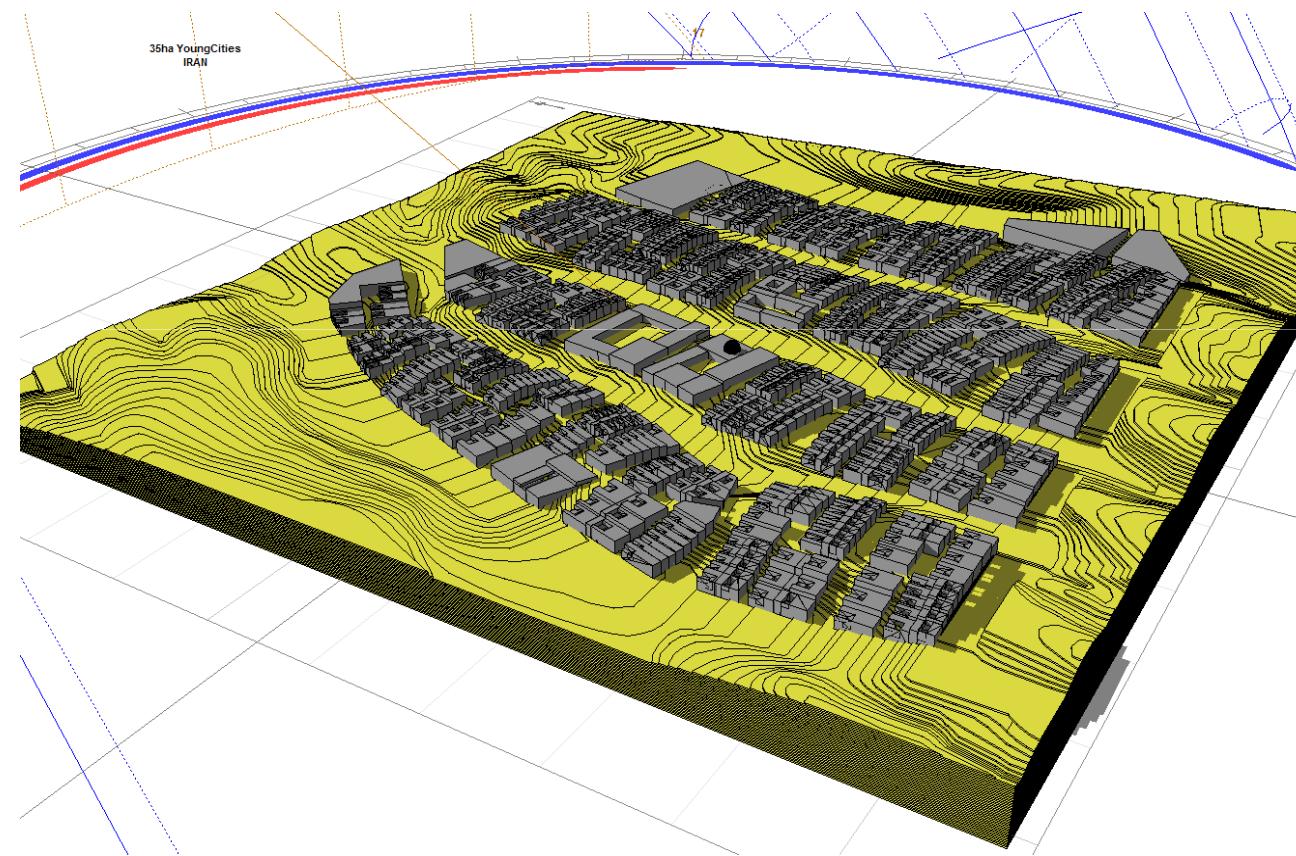
Velocity distribution for the heating case (location Berlin)



# Multiscale Simulation – Example: City district hierarchy

## Research project „Young Cities“ (2008-2013):

Development of an energy efficient district with 2,000 living units on a 35 ha area within the New Town Hashtgerd (Iran)



Digital urban model of the 35 ha Pilot area in Hashtgerd, Iran



Location of the New Town Hashtgerd/Iran



New Town Hashtgerd/Iran (buildings of the first construction phase 1990 - 2000)



# Multiscale Simulation – Example: City district hierarchy

## – Sub-project UdK Berlin

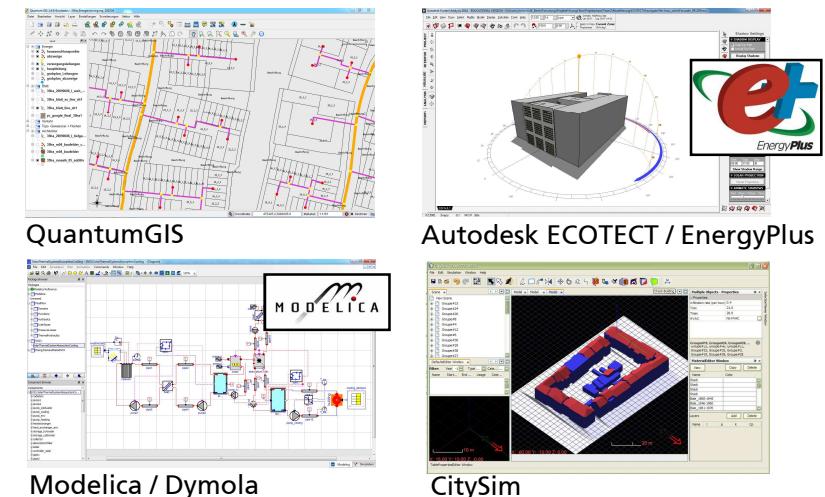
- Modelling of the heating and cooling demand of the new planned buildings on the 35 ha area
- Simulation based design of variations of central, semi-central and de-central energy supply systems (heating, cooling, electricity)

## – Used calculation methods

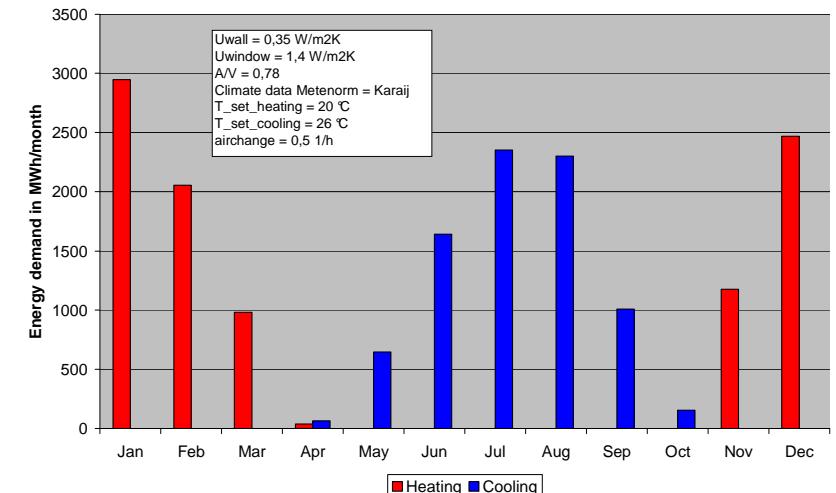
- Geographical Information System (GIS)
- Integrated transient system simulation of buildings and energy plants
- Short-time and year simulations:
  - Irradiation, shadowing and thermal comfort analysis
  - Function tests and energy management
  - Heating and cooling loads and demands
  - Primary demand and CO<sub>2</sub>-emissions

## – Overall loads of the 35 ha area:

- Heating :14,5 MW; Cooling:12,0 MW



Used simulation and calculation tools



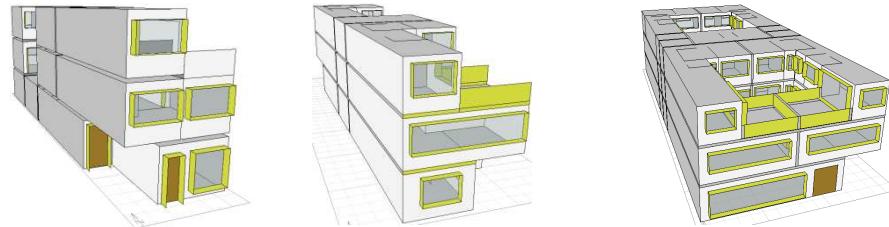
Heating and cooling energy demand of the 35 ha area



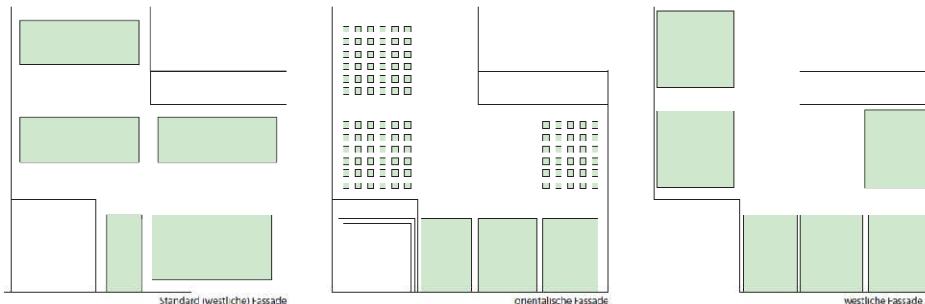
# Multiscale Simulation – Example: City district hierarchy

## Energy demand analysis (Autodesk ECOTECT /EnergyPlus)

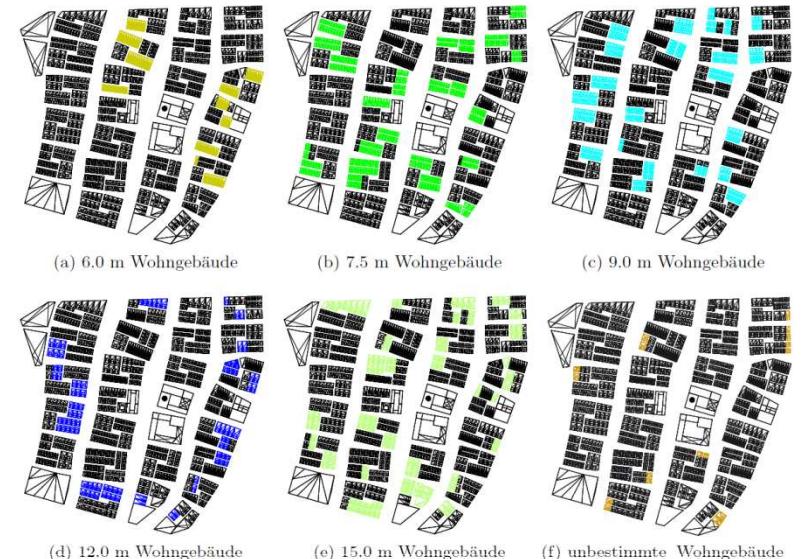
- Analysis of variations of building types and facades:



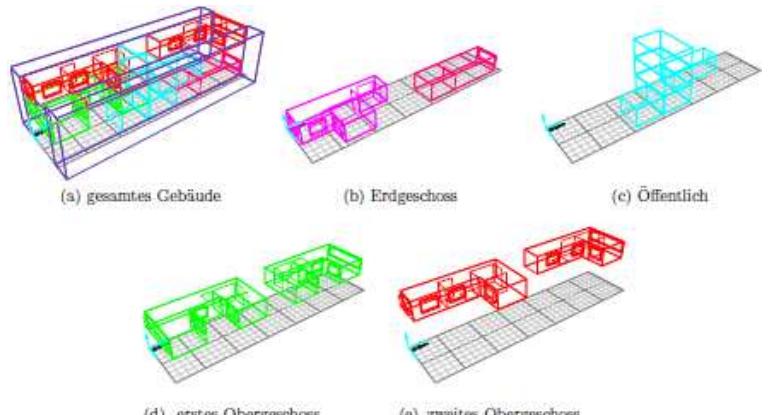
Different building types (6m up to 15m width of the facade)



Comparison of different facade openings within one building type  
(e.g. 9m building)



Distribution of the building types on the 35 ha area



Thermal zoning of the building types (e.g. 9m building)



# Multiscale Simulation – Example: City district hierarchy

## Energy Supply System B:“Centralized Cogeneration / Local Solar Cooling”

### Energy Central

- CG Gas-Cogeneration plants
- SAC Small absorption chillers
- STC Solar thermal collectors

### Energy storages

- HS Central heat storages

### Energy distributor

- District heating net

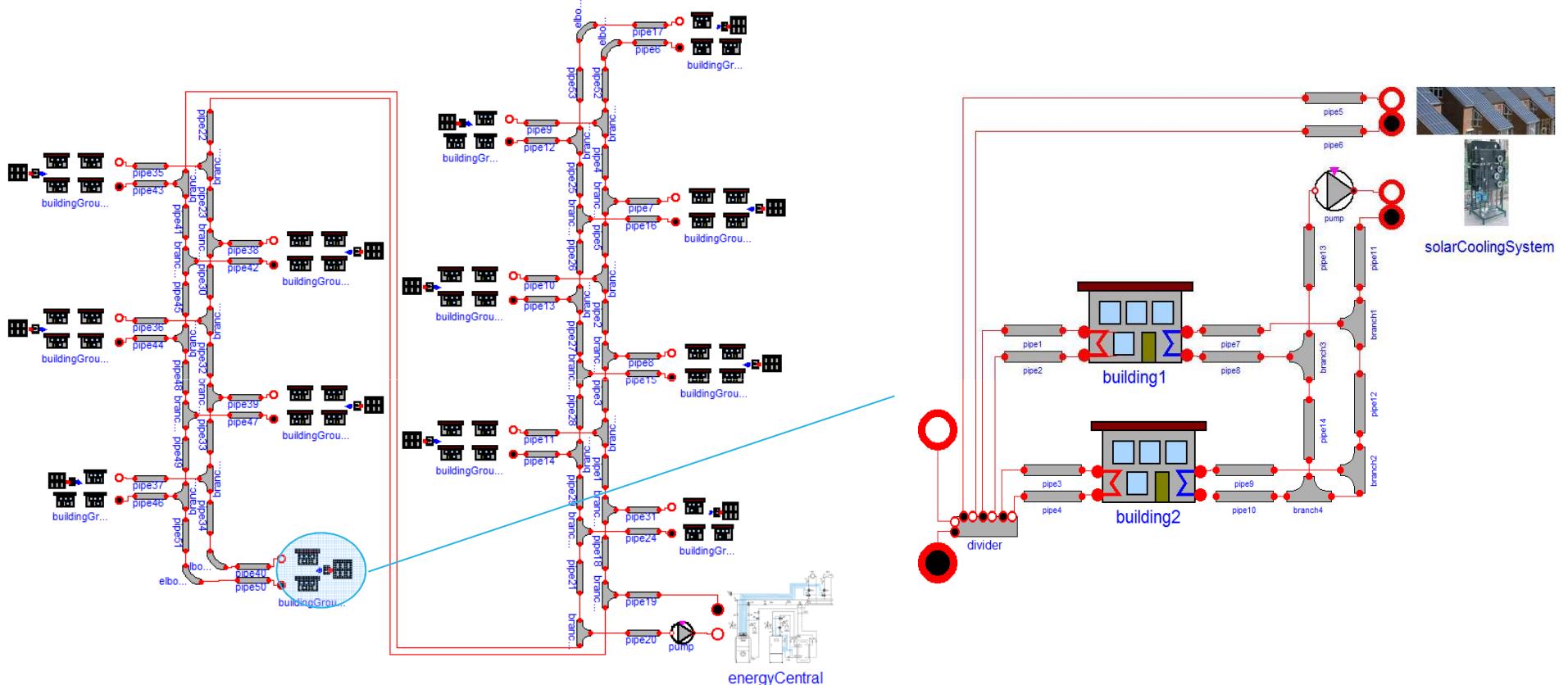
### Energy consumers

- Residential houses
- Office buildings
- Educational buildings
- Culture buildings
- Religion buildings



# Multiscale Simulation – Example: City district hierarchy

## System simulation with Modelica / Dymola

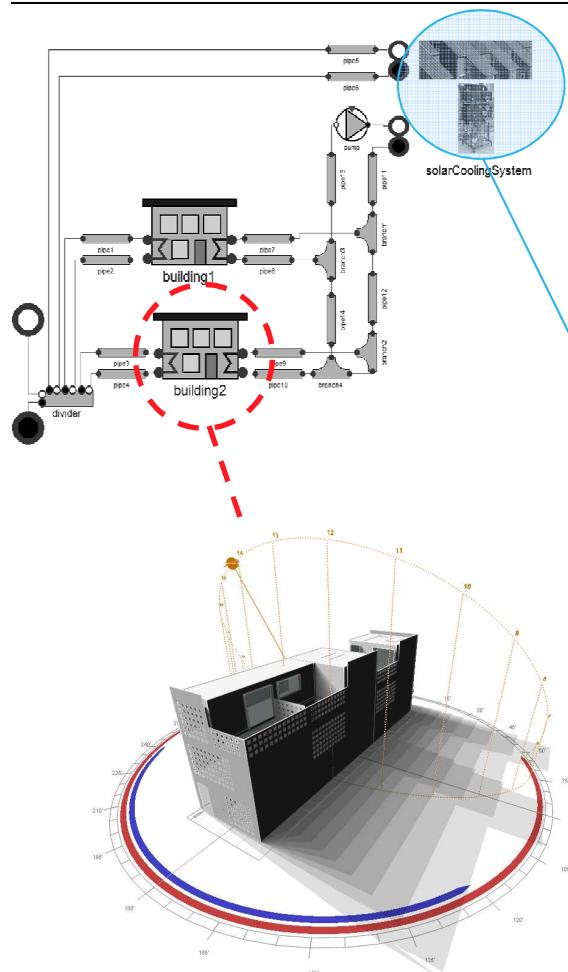


System model with a centralized heat supply and decentralized solar cooling

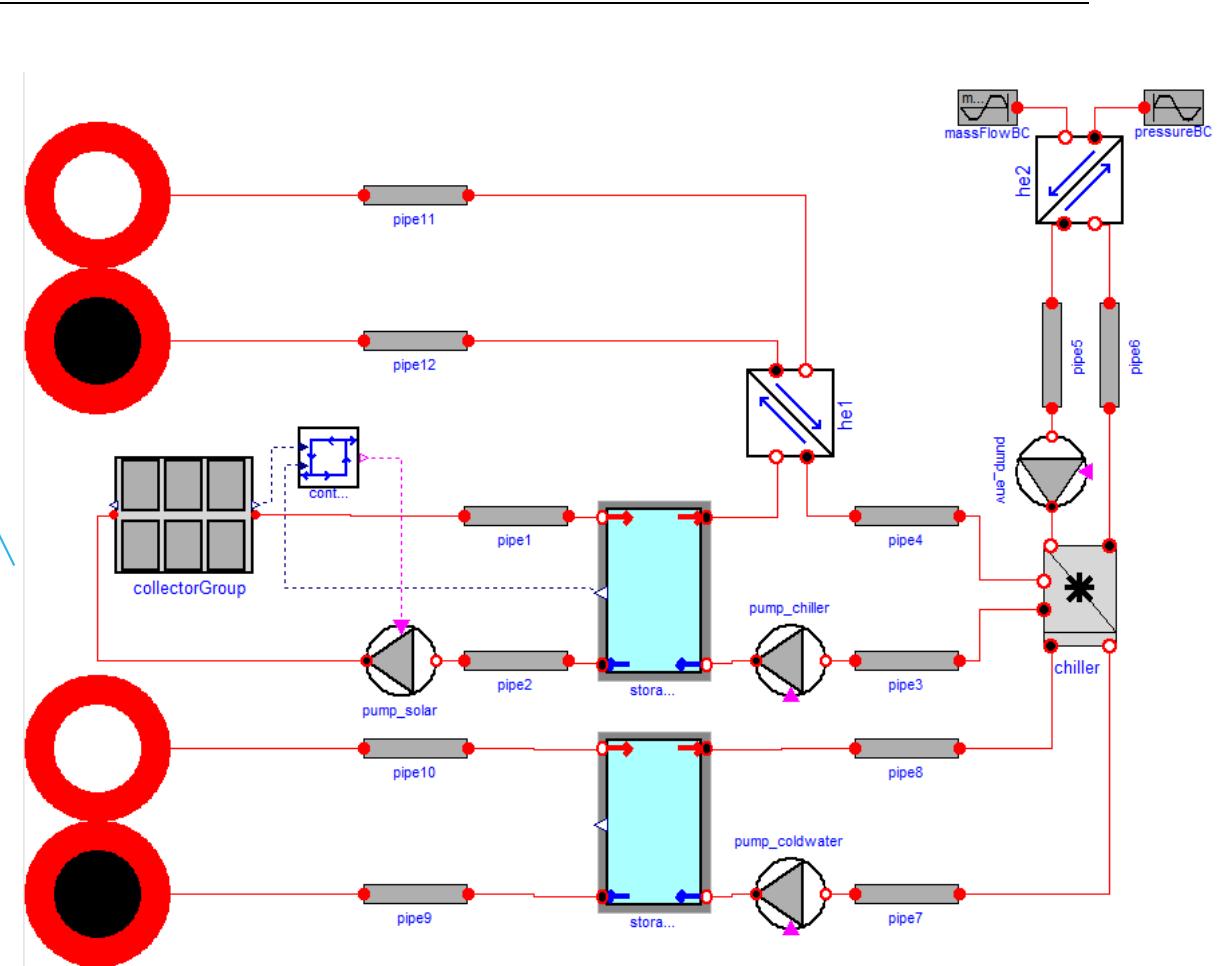
Sub-model with thermal load models (building group) and a solar cooling system



# Multiscale Simulation – Example: City district hierarchy



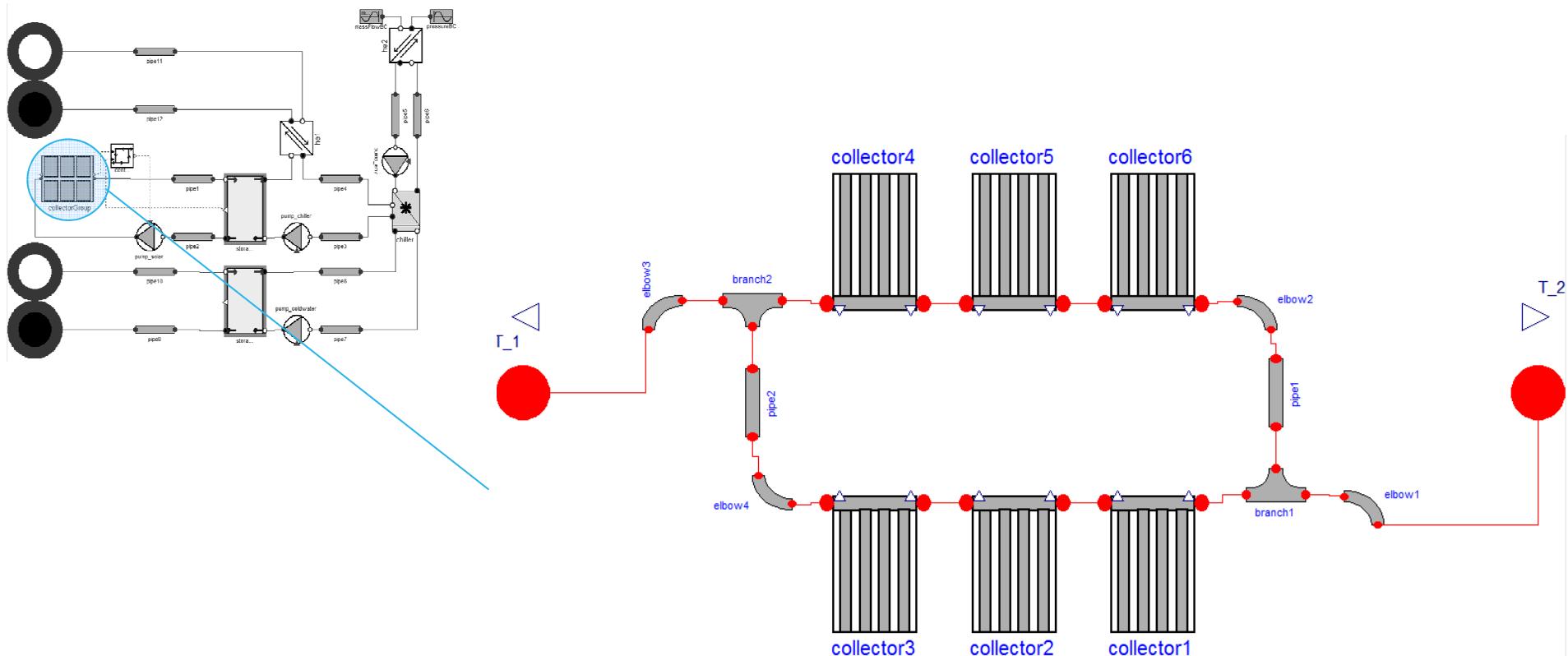
Energetic optimization of the residential building types, based on ECOTECT/EnergyPlus



Sub-model of the solar cooling system with solar heat production, absorption chiller and thermal heat and cold storages



# Multiscale Simulation – Example: City district hierarchy

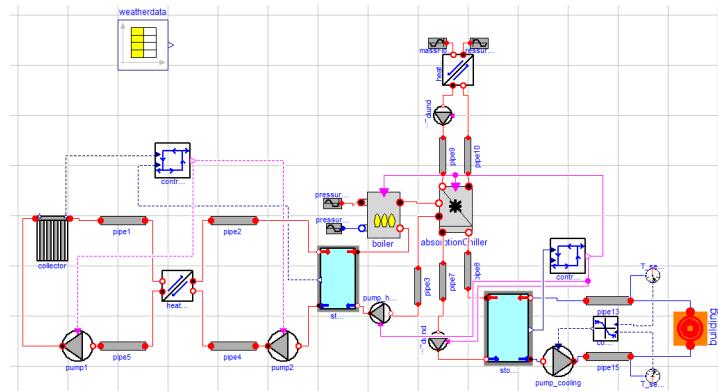


Sub-model of the solar thermal collector field



# Multiscale Simulation – Example: City district hierarchy

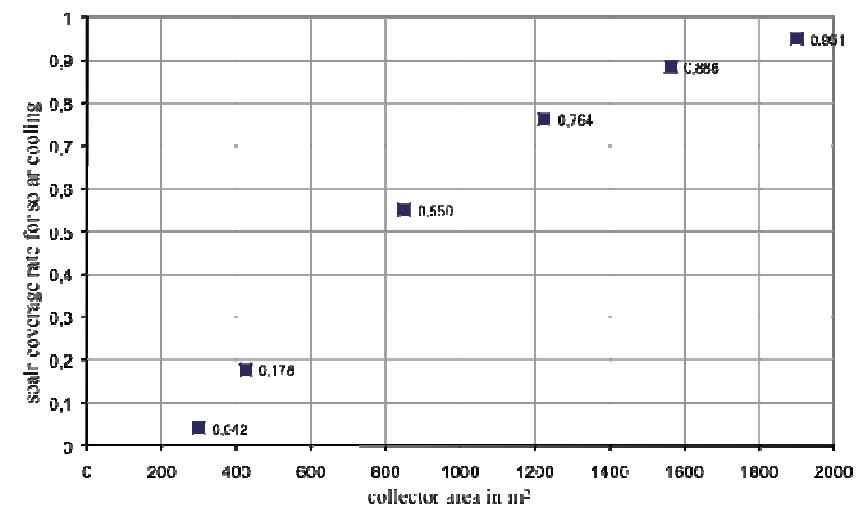
- Potential analysis of the solar cooling system for a selected sub-neighbourhood
  - Climate: outside air temperatures up to 40 ° C and a solar irradiation of 1,900 kWh/(m<sup>2</sup>a)
  - Detailed modelling of the thermal loads and the energy supply system (solar thermal cooling system with absorption chillers)
- Results of the simulation analysis
  - A solar coverage rate near to 100 percent is possible using the given roof area potential



Modelica simulation model of the solar thermal cooling plant



Analysed sub-neighbourhood (SN 32)

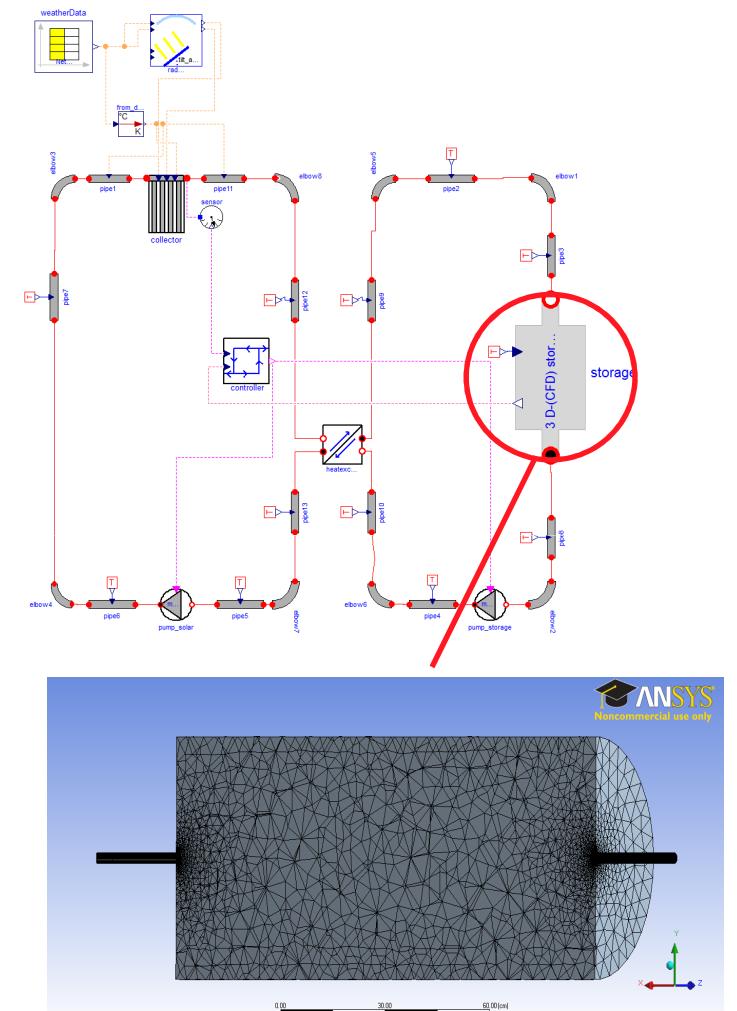


Solar coverage rate as a function of the collector area



# Co-Simulation - Numerical coupling of 1D- and 3D-models

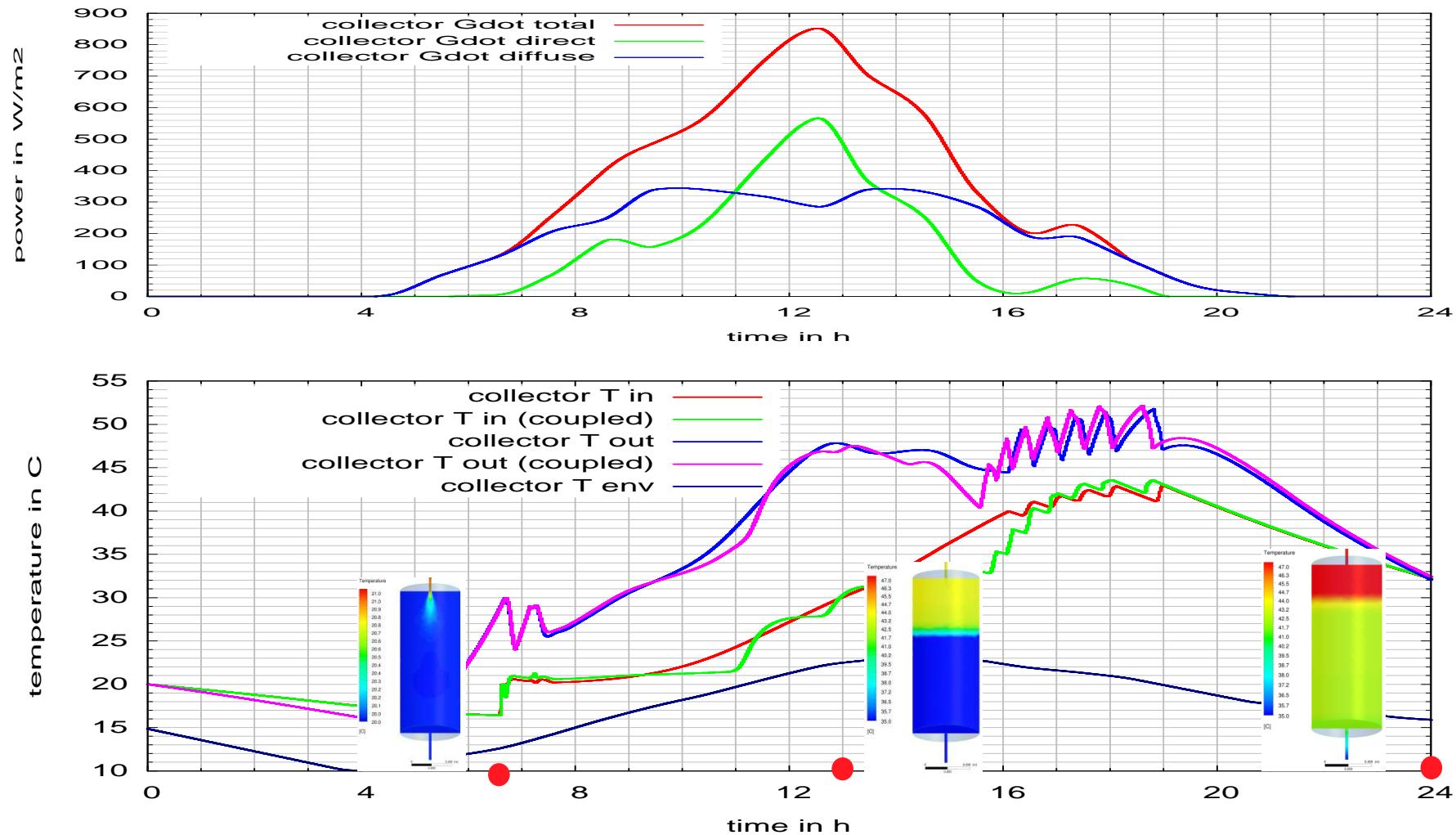
- Example: Model of a solar thermal system, based on the Modelica-library *BuildingSystems*
- Technical realisation of the co-simulation
  - Simulation Tools: Dymola 7.4 & ANSYS CFD 12.1
  - Numerical coupling with middleware TISC
  - Synchronisation rate: 1 second
- Model sizes and coupling:
  - DAE-system of the solar thermal system without the heat exchanger: 604 equations after translation
  - CFD-Model of the hot water model: 72.000 finite-volume-elements
  - Coupled model variables: mass flows, pressures, temperatures
- Simulation experiment
  - Charging process of the solar thermal system during a sunny summer day (24 hours real time)
  - Calculation time: ~ 2 days (use of 8 core parallel processors)



Coupled Modelica / ANSYS CFD-system model



# Co-Simulation - Numerical coupling of 1D- and 3D-models

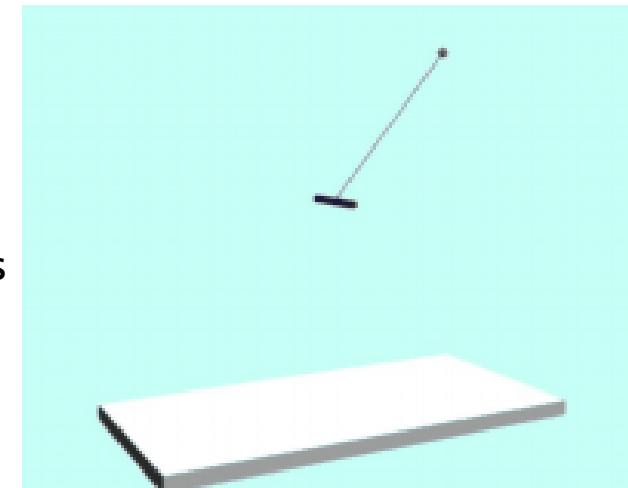


Solar irradiation on the collector (above) and the collector inlet and outlet temperatures for the pure Modelica-system model and the coupled Modelica / ANSYS CFD system model in comparison (below) during a summer day in June

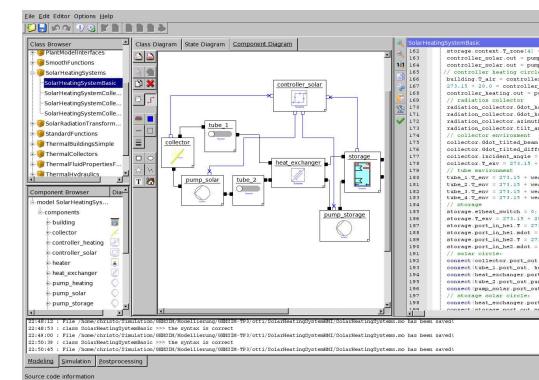


# Adaptive Simulation – Model structural dynamics

- **Model structural dynamics (MSD):**
  - Approach, which can change size and structure of the DAE-system during the simulation runtime, depending on the model state itself (e.g. string pendulum) or on deterministic events
  - Adaptation of the physical description of the model or its resolution in space
- **Modelica language extension for MSD**
  - Dynamical objects
  - Object-oriented statecharts (states, transitions)
  - Dynamical connectors
- **Modelica simulation tool MOSILAB for MSD**
  - Result of a joint project of several Fraunhofer-Institutes between 2004 and 2007
  - Supports Modelica 2.x
  - Compiler for Modelica 3.x/4 is being developed



2D-string pendulum: changes between the model states *stretched* (degree of freedom "rotation angle") and *flying* (degrees of freedom "x and y")

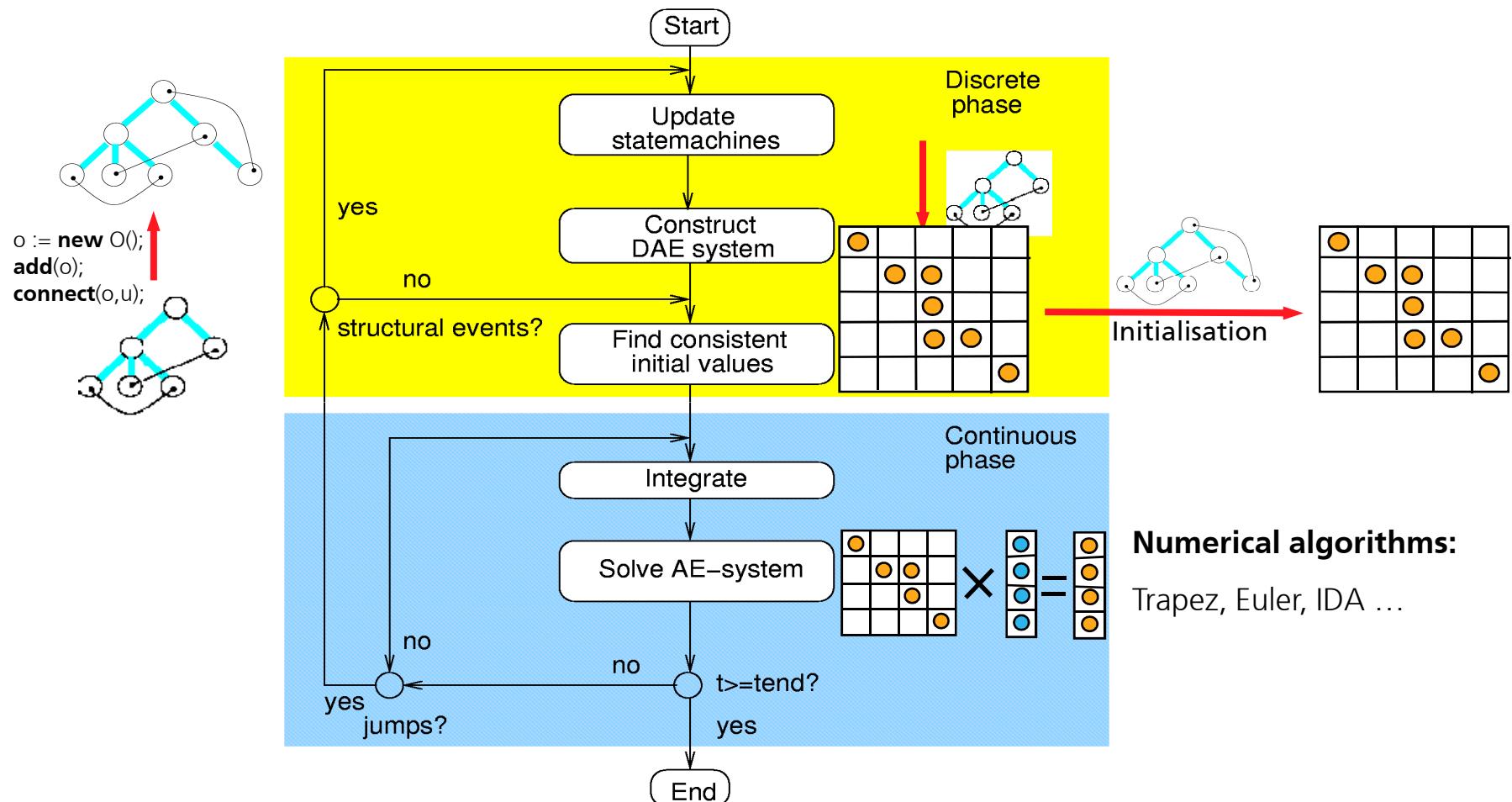


Simulation tool MOSILAB from the Fraunhofer Gesellschaft (<http://www.mosilab.de>)



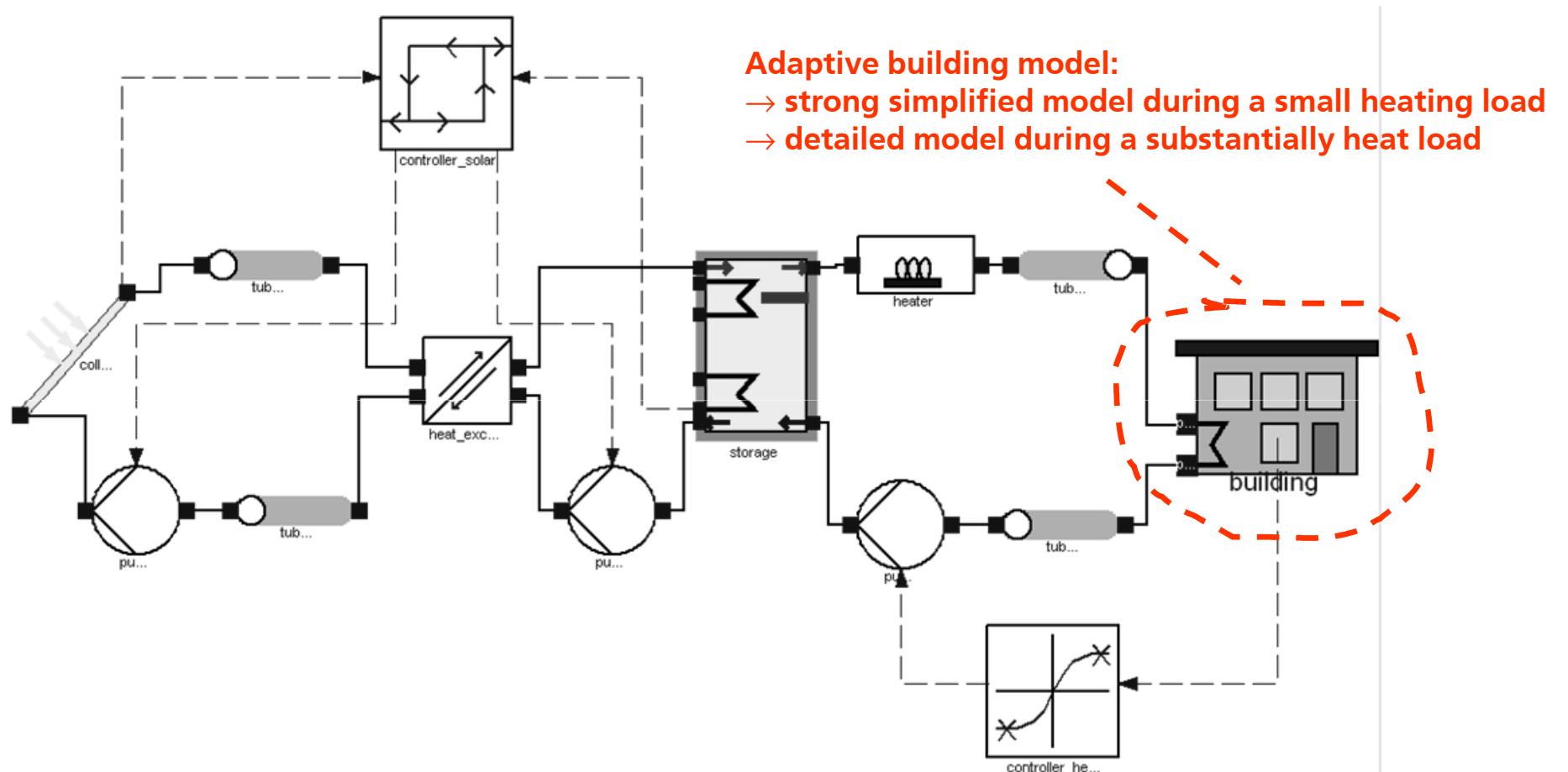
# Adaptive Simulation – Model structural dynamics

## Realisation of the Model Structural Dynamics within MOSILAB



# Adaptive Simulation – Model structural dynamics

## Example: Solar heating system with an adaptive building model

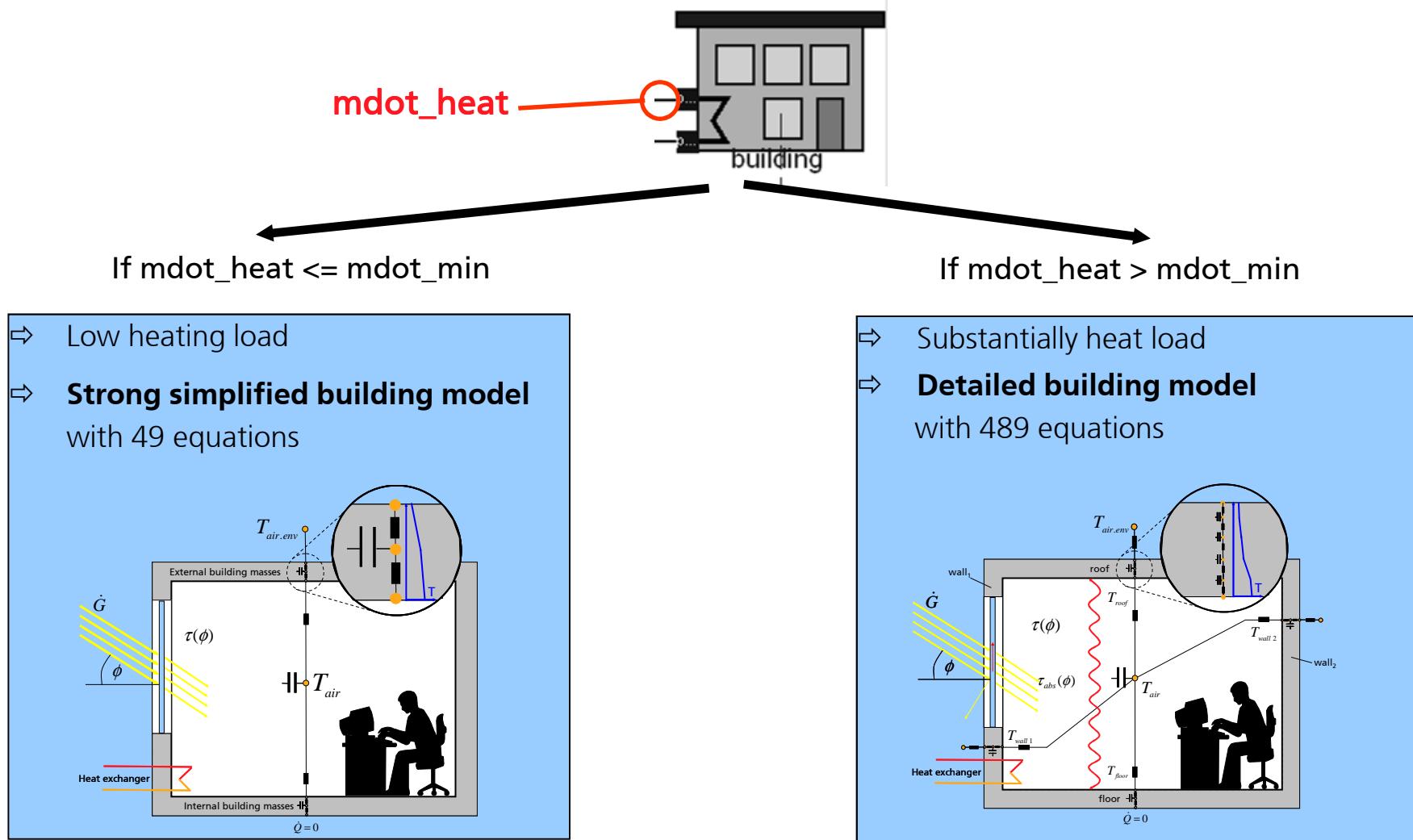


**Problem: Transferred heat flow Qdot\_heat between heating loop and building model**



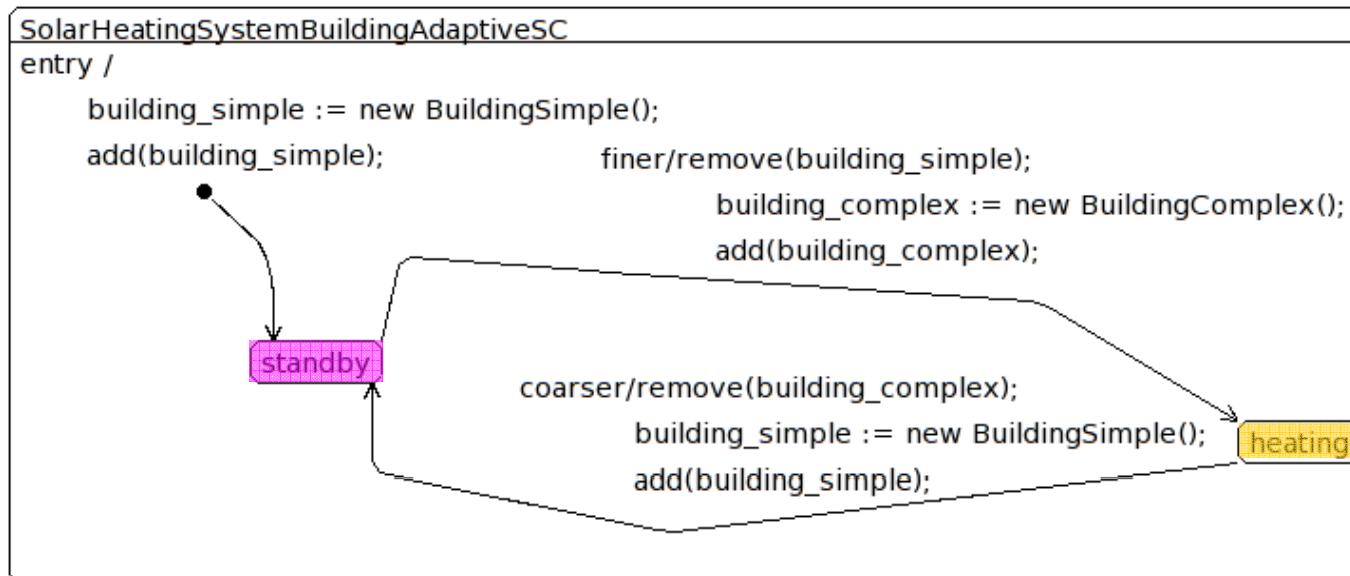
# Adaptive Simulation – Model structural dynamics

## Example: Solar heating system with an adaptive building model



# Adaptive Simulation – Model structural dynamics

## Example: Solar heating system with an adaptive building model



1. Definition of the states **standby** and **heating**
2. Definition of the event-equations **finer** and **coarser** as functions of **mdot\_min**
3. State-depend use of the strong simplified or detailed building model

**Constraint:** Conservation of energy after state changes:

$$\text{Refinement: } \sum_i m_i \cdot c_i \cdot T_{start,i} \equiv m \cdot c \cdot \bar{T}_{old} \quad \text{Coarsening: } m \cdot c \cdot \bar{T}_{start} \equiv \sum_i m_i \cdot c_i \cdot T_{i,old}$$

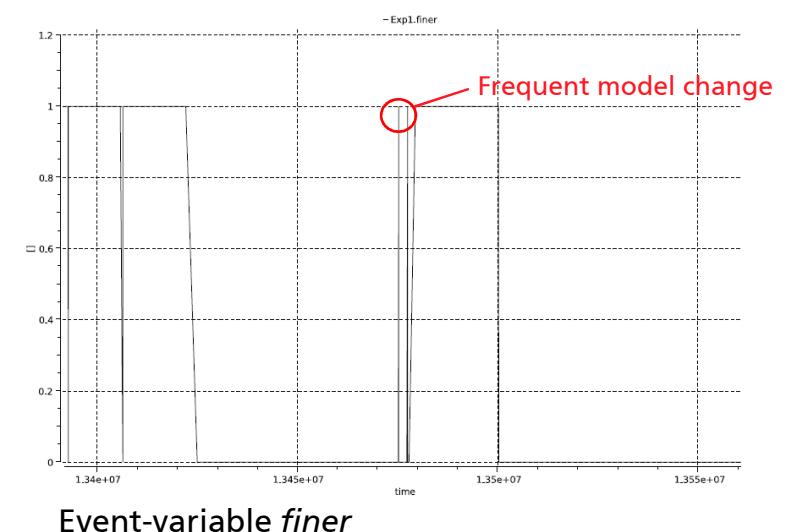
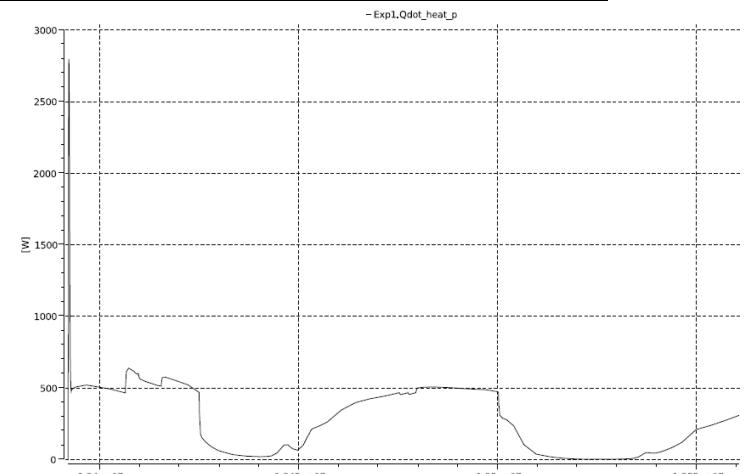


# Adaptive Simulation – Model structural dynamics

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## Use of the approach of adaptive building models

- **Model exchange between the system states inclusive re-initialisation works fine**
- **CPU-time over an period of two summer days (155. u. 156. day of the year):**
  1. Only the detailed model: 100 % CPU-time.
  2. Only the simplified model: 4.5 % CPU-time.
  3. Adaptive model: 57 % CPU-time
- **Course of the heating load is very similar for all three variants**
- **Problem, which has to be solved:**
  - A frequent model change leads to increasing simulation time, because the adaptive time step algorithm starts with small time steps after each model exchange



# Outlook

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## – Individual Roadmap

- Deepening the collaboration in Open Source Modelica-library development for building and plant simulation
- Improvement and partly redesign of our Modelica-libraries regarding more flexibility in different levels of detail
- Gain more experience in co-simulation methods
- Development of more complex examples of adaptive system models

## – Political Agenda

- Introduction of PDEs into Modelica
- Introduction of MSD into Modelica
- Strong improvement of the Open Source Modelica-tools (OpenModelica, JModelica)

